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Reevaluation of Window-Cooling Test Data: HEDI Window-Cooling Test in the AEDC HR Arc Heater*

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Abstract

Multiple experiments were conducted in the late 1980's and early 1990's to determine the effectiveness of transpiration and film cooling on the temperature control of an infrared (IR) seeker window during a missile's hypersonic flight. These efforts were made in support of the United States Army Space and Strategic Defense Command (USA SSDC) High-Endoatmospheric Defense Interceptor (HEDI) program. The experiments were designed as a series of complementary tests in several facilities that would provide the data necessary to predict window-cooling requirements. Recent emphasis on a similar missile system program, Atmospheric Interceptor Technology (AIT), has prompted a reevaluation of the HEDI database of ground test data and led to new analysis of experimental results from one of the high-temperature facilities, Arnold Engineering Development Center's (AEDC) HR arcjet. While the HR test objective was oriented toward survivability issues and was conducted at a smaller scale (40 percent vs. 75 to 100 percent) and different geometry (2-D wedge vs. tetracone), window-cooling effectiveness results are in excellent agreement with other national facilities and the literature. Comparisons of the window-cooling data from AEDC Tunnels B and C, Calspan Hypersonic Shock Tunnel (HST) and HEDI facilities, AEDC/Naval Surface Warfare Center (NSWC) Tunnel 9, and AEDC HR are presented. In addition, the film-cooling effectiveness parameter, freestream turbulence, test article scale, and window-cooling breakpoint are discussed. Finally, new AEDC high-temperature facility capabilities are presented.

Nomenclature

- h Heat-transfer coefficient
- h′ Total height of coolant slot and lip
- M Mach number
- Re Reynolds number
- s Coolant slot height
- S* Modified cooling correlation parameter, Eq. (1)
- x Distance downstream of slot
- λ Mass flow ratio $(\rho V)_c/(\rho V)_\delta$
- μ Viscosity
- η Film-cooling effectiveness
- ρ Density
- γ Gas specific heat ratio
- ζ Film-cooling correlation parameter

Subscripts

- aw Adiabatic wall conditions
- c Coolant
- e Edge
- ∞ Freestream conditions
- δ Boundary-layer edge conditions
- r Reference conditions
- T_c Coolant total temperature
- T_∞ Freestream total temperature
- w Wall conditions

Introduction and Background

Hypersonic interceptors typically use infrared (IR) sensors for targeting. Because of this, a viewing window must be used which remains transparent to IR throughout the operational flight envelope of the missile. For endoatmospheric interceptors, the window must maintain its optical transparency and be thermostructurally sound in the severe

* The research reported herein was performed by the Arnold Engineering Development Center (AEDC), Air Force Materiel Command. Work and analysis for this research were performed by personnel of Sverdrup Technology, Inc., AEDC Group, technical services contractor for AEDC. Further reproduction is authorized to satisfy needs of the U. S. Government.

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hypersonic environment. Active cooling is employed to maintain a low temperature gradient throughout the seeker window, minimizing gradients in the index of refraction that can lead to image blurring. More importantly, maintaining a low window temperature reduces the radiation from the window into the sensor, which reduces the signal-to-noise ratio.

Film cooling is an effective method of maintaining the seeker window temperature requirements while providing a wide field of view for the sensor. When the coolant gas is injected tangentially into the turbulent boundary layer from a slot upstream of the window, the coolant provides an insulating layer and practically eliminates heat transfer to the window for some distance downstream from the injection slot. In addition, a transpiration-cooled frame is employed around the seeker window in order to control the temperature of the window support structure and obviate the need for passive ablation materials, which could degrade visibility with their ablation products.

Experimental determination of the effectiveness of the film cooling has been sought for a wide range of environmental conditions and missile configurations. This is necessary to determine the amount of coolant required for each specific configuration and to provide a significant database of ground-test data that will allow confident extrapolation to flight conditions.

One such effort was conducted in the late 1980's and early 1990's as part of the United States Army Space and Strategic Defense Command (USA SSDC) High-Endoatmospheric Defense Interceptor (HEDI) program. The methodology to predict window-cooling requirements began with the gathering of data from a wide range of hypersonic facilities listed in Table 1.

Upon completion of the AEDC and Calspan tests, the design and cooling requirements were determined. At this point in the program, enough data had been gathered to develop an empirical and universal correlation parameter [presented below as Eq. (1)]. Rather than use the entire effectiveness curve, a simplification called the 'breakpoint analysis' was introduced. This involves projecting the undercooled data until it intersects the completely cooled effectiveness line, thus determining the 'breakpoint' between undercooled and overcooled. Compiling the breakpoints for various configurations and test conditions is expected to enable establishment of the minimum requirements for complete cooling.

Subsequently, a full-scale forebody was tested in the Naval Surface Warfare Center's (NSWC) Tunnel 9 to confirm flight-cooling requirements. [1] This was followed by testing in the Calspan Hypersonic Shock Tunnel (HST) after modification to provide aero-optics testing in support of the HEDI program (Table 2). This test entry is referred to here as Calspan-HEDI to distinguish it from the earlier Calspan HST test entry. The test conditions were matched as closely as possible to the Tunnel 9 conditions.

A review of the window-cooling literature confirms that the amount of ground test data that represent flight temperatures and heat fluxes in the hypersonic regime is quite limited due to the limited number of facilities that operate at these extreme conditions. Reevaluation of the HR arcjet data was

Table 1. HEDI Program Test Objectives

Test	Facility	Primary Objective	Scale
Coolant Performance	Acurex/Aerotherm APG	Evaluate design parameters/Coolant Selection	Coupon
Slot-Cooling Performance	AEDC Tunnel B	Establish slot-cooling performance HEDI database	75%
Window-Cooling Performance	AEDC Tunnel C	Compare slot- and grid-cooling performance	75%
Window-Cooling Performance	Calspan HST	Confirm window-cooling requirements	75%
Window-Cooling Thermal Performance	AEDC HEAT-HR	Survivability of platelet forebody, window frame, and sapphire window	40%

Table 2. HEDI Program Test Objectives – Full Scale

Test	Facility	Primary Objective	Scale
Window-Cooling Performance	NSWC Tunnel 9	Confirm window-cooling requirements for flight design	100%
Facility Validation	Calspan-HEDI	Validate Calspan facility for aero-optic testing	100%

undertaken to determine how the subscale, 2-D test correlates with the established hypersonic database and the open literature. Good correlation of the HR data validates other AEDC high-temperature, arc-heated facilities for cooling effectiveness tests.

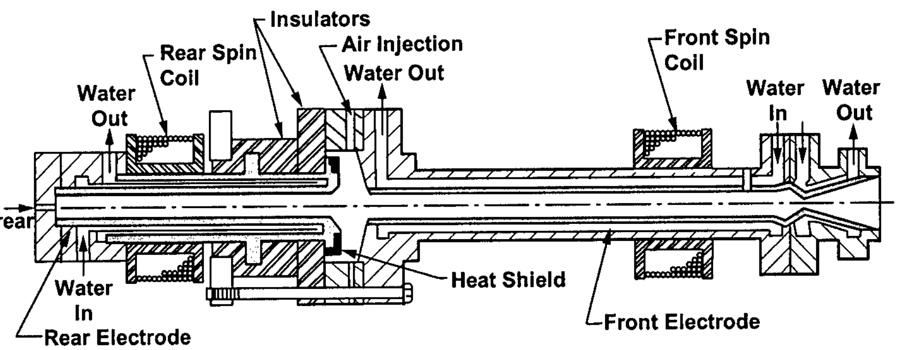


Fig. 1. AEDC HR test unit.

HEAT-HR Test Facility and Window Model

The AEDC HR test unit is one of four continuous-flow, arc-heated test units which comprise the AEDC arc heater facility. It is located in the AEDC High Temperature Laboratory. The HR Test Unit produces a high-pressure, high-enthalpy supersonic freejet flow field for ablation testing of advanced nosetip and heat shield materials, as well as for other high-pressure/high heating rate tests such as transpiration-cooled nosetips or leading-edge test articles. The HR Test Unit is currently maintained in mothball status having been replaced by the arc facilities discussed below. A schematic is given in Fig. 1.

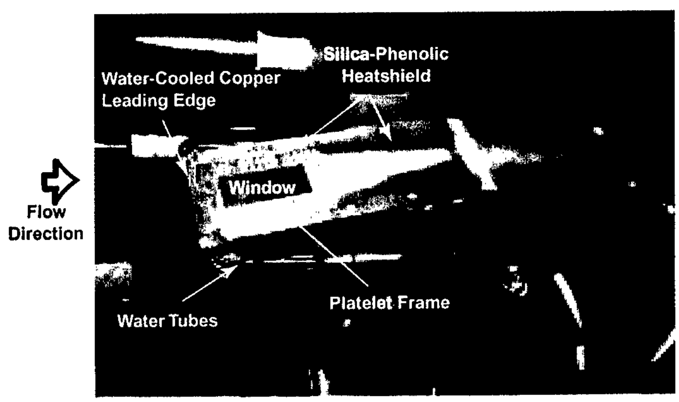


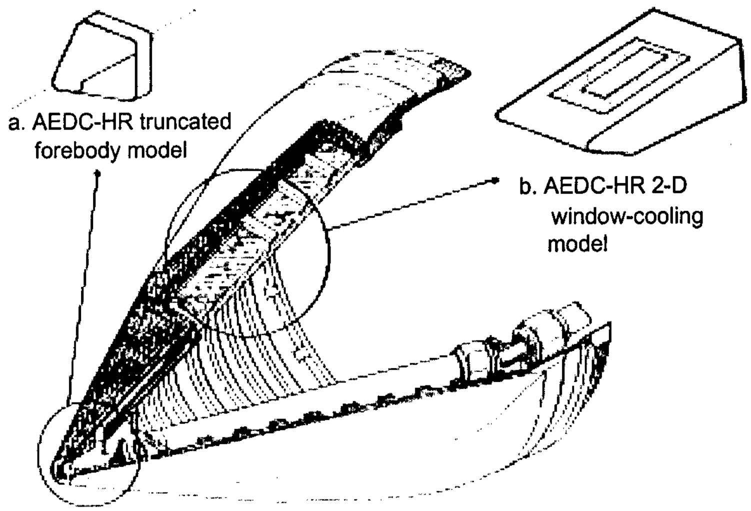
Fig. 2. Slot window-cooling model installation - AEDC HR.

The design of the test model was based on information derived from facility calibration data and CFD analysis. The information was used to optimize the test model geometry and location in the flow field, as well as facility operating conditions and nozzle requirements. The HEDI forebody seeker window region was scaled to 40 percent (1.5 in. wide by 3.5 in. long) to fit within the facility flow field. The window was mounted in a transpiration-cooled platelet frame held in the flow field by a water-cooled model holder.

Two test models were mounted on the HR rotary positioning system, and the coolant supply system was capable of three flow rates to each model, providing six steady-state test points per test run. Six window-cooling test runs were performed during the HEDI test program. A photograph of the HR test model is shown in Fig. 2.

As shown in Table 1, the primary objective of the AEDC HR test was to demonstrate window survivability, not to develop a film-cooling correlation. The HR test model differed from that used in the other

facilities (Tunnels B, C, and 9, and the Calspan shock tunnel). The HR model was a 2-D wedge of 40-percent scale, while the other facilities used a 75- to 100-percent scale model having a tetracone nose similar to that of the flight vehicle (Fig. 3). As a result, the HR model did not duplicate either the boundary-layer buildup prior to the injection of the film coolant or the 3-D character of the model. Although a significant number of coolant flow rates and model configurations were tested, the data from the HR series were not analyzed relative to a "cooling correlation."



c. HEDI forebody concept

Fig. 3. HEDI forebody model design.

Results

Reexamination of Test Data

It was possible to retrieve enough of the HR-HEDI test data to compute the necessary window-cooling parameters even though the test was performed over thirteen years ago. As a first step, the data were compared to other results from the literature. A survey paper by Goldstein[2] contains a large amount of film-cooling data for various configurations from various sources. Data for a supersonic flow are presented in Fig. 20 of Ref 2. These data are represented as a bounded band in Fig. 4; the HR-HEDI data have been added to Fig. 4 and are seen to fall within this data band. It is also noted that the HR data are largely overcooled (i.e., most of the data show an effectiveness of greater than 0.95). Only a few of the data points begin to show a breakover into the declining effectiveness typical of the undercooled condition. Hence the HR data have limited utility for a 'breakpoint' determination. This is discussed in more detail below.

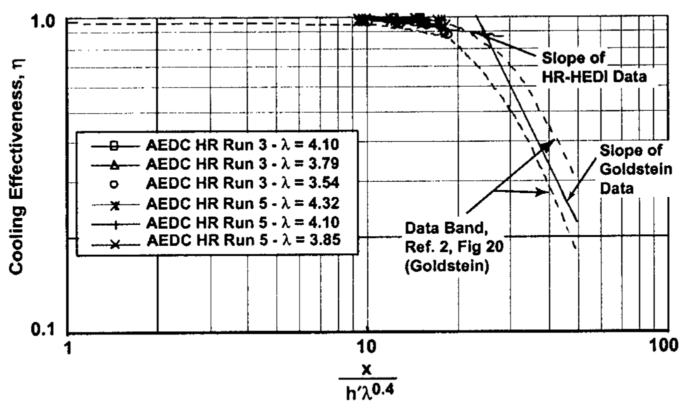


Fig. 4. Comparison of Goldstein and HR-HEDI windows-cooling data.

Development of Film-Cooling Parameter

The development of the HEDI film-cooling parameters has been documented in a series of AIAA papers (Refs. 1 and 3 are representative). Early attempts used a relatively simple (but somewhat standard) correlation parameter, $x/(s\ \lambda)^{0.8}$, where λ is the ratio $\rho_c V_c/\rho_e V_e$. It was noted in Ref. 1 that some scatter was present due to Mach number and angle-of-attack sensitivities. Reference 1 also notes that the data tended to shift to the left as the total enthalpy of the facility flow increased. This is shown in Fig. 5 with a comparison of facilities of increasing enthalpy, Tunnels B, C, Calspan HST, and AEDC-HR, respectively.

Efforts to remove these dependencies are documented in Refs. 1 and 3. These efforts culminated in the development of the correlation parameter:

$$S^* = (x/s\lambda)(Re_c\mu_c/\mu_e)^{-0.25}(\rho_c/\rho_e)^{0.4}(\mu_e/\mu_c)^{0.75} \left(1+(\gamma-1)/2M_c^2\right)^{-0.5} \quad (1)$$

Data from various facilities were compiled using this correlation and are compared and discussed in the following section.

Data Comparison

The cooling effectiveness data from Tunnels B and C and Calspan HST are plotted versus S* in Fig. 6 of Ref. 1 and are seen to coalesce quite well. These data are shown here as a band in Fig. 6 with the HR data added. It is noted that there is good agreement between the HR data and Tunnels B, C, and Calspan HST.

The Tunnel 9 and the later Calspan-HEDI data are also compared and are plotted versus S* in Fig. 7. Again, there is good agreement between HR, Tunnel 9, and Calspan-HEDI. As shown in Table 3, the total temperature is not correctly simulated in any of the facilities; however, the correlation [Eq. (1)] does an adequate job of removing this dependence.

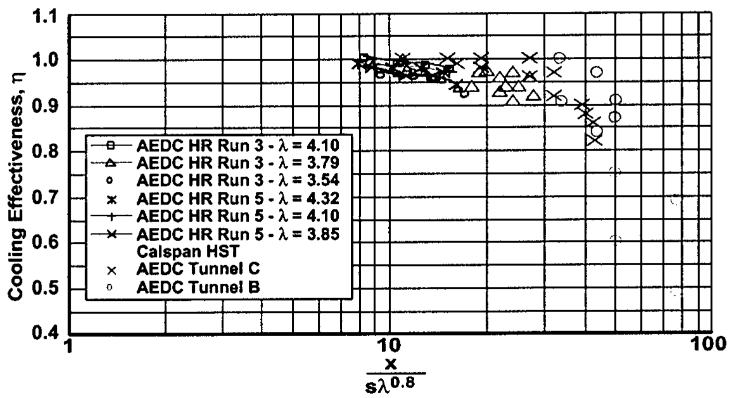


Fig. 5. Initial cooling effectiveness correlation.

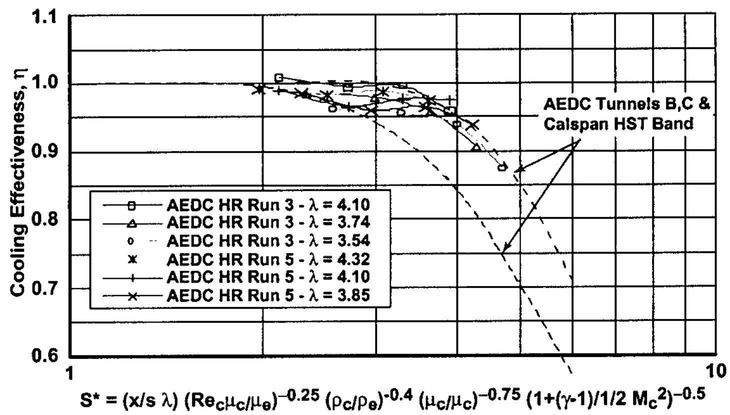


Fig. 6. Comparison of Tunnels B, C, and Calspan HST data and HR-HEDI window-cooling data.

Discussion

As stated in the abstract, a key focus of this paper is to reevaluate test data obtained with the AEDC arc-heated test unit HR. Validation of this high-temperature facility for cooling effectiveness testing leads to high-productivity, subscale ground tests. Larger models can be used in the new, larger AEDC arc heater, H3. This facility can provide a considerably larger test section at higher performance and will be presented in the discussion section of the paper.

Discussion of 'Breakpoint'

As mentioned previously, the breakpoint is used to mark the boundary between a fully cooled and an undercooled condition in a film-cooling application. The breakpoint can be a useful engineering parameter, but one must be careful in both use and determina-

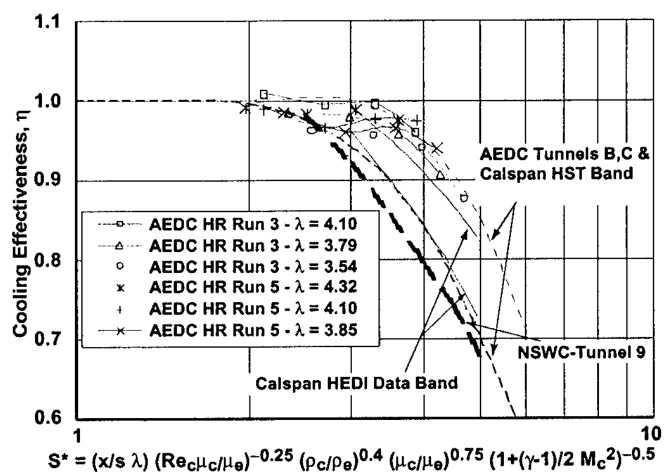


Fig. 7. Comparison of Calspan HEDI and HR-HEDI window-cooling data.

tion. The straight line (on the log-log plot) shown in Fig. 4 (Eq. 55, in Ref. 1) is a fit to the undercooled data. Extrapolating this line to a cooling effectiveness of 1.0 defines a breakpoint. Note that the data do not go through the breakpoint but transition smoothly from the overcooled to the undercooled regime.

Also note that the HR-HEDI data, even though they fall on top of the other data, do not help define the breakpoint. In order to define the breakpoint, one must have a significant amount of undercooled data to fix the slope (effectiveness 80 percent and less). If one were to use only the data in the transition region between the fully cooled and undercooled conditions (the "knee" of the curve) to define a breakpoint, one could not expect that breakpoint to agree with breakpoints determined from significantly undercooled data (see Fig. 4). It is noted, however, that data in the "knee" region would yield a conservative (low) value for the breakpoint. Examination of Figs. 6 and 7, where the HR-HEDI data are shown in addition to the other HEDI data, leads to the same observations and conclusions; i.e., the HR-HEDI data agree with HEDI data from other facilities but are not useful for defining a breakpoint. The test objective was to demonstrate survivability; hence the test matrix ventured only very tentatively into the undercooled regime. Unlike the low heat flux facilities, the danger of model burn-up was very real in the HR facility. Venturing too far into the undercooled regime would have resulted in model failure.

Reference 1 states in its conclusions that "...there is still a sensitivity of the correlation toward reduced effectiveness with higher total temperatures." A review of Ref. 1 reveals that this analysis is based solely on the breakpoint calculated from curve-fitting the correlation parameter to the cooling effectiveness from the various facilities (Table 3). There is a fair amount of variation in the breakpoints even though the data are quite consistent (see Figs. 4-6). This variation in the breakpoint is influenced as much by where the data were taken (overcooled versus undercooled) as it is by differences in the facilities. In fact, the composite data yield the best breakpoint to use for optimizing missile window-cooling requirements as opposed to some value extracted from the disparate breakpoints from the individual facilities (Table 3).

Simulation Parameters

Correlation Requirements

The reexamination of the HR-HEDI test data has shown that the differences in scale (40 percent vs. 75 to 100 percent) and geometry (2-D wedge vs. tetracone) have little effect on the results. However, as a parametric study was not performed, it is possible that compensating effects may be involved. The correlations developed by MDAC and Goldstein are fairly insensitive to Mach number and freestream Reynolds number and can account for the differences in scale. Reevaluation of the HR data also shows that these parameters are not critical for determining window-cooling effectiveness and that optimization of the test model to the smaller arcjet facility nozzles does not affect the test results.

Table 3. Flight Heat Flux compared to Facility Heat Fluxes

Test	Heat Flux (Btu/ft^2 sec)	Total Temp, °R	Facility Break Points (S^* Intercept @ $\eta = 1$)
HEDI Flight	1100	5800	- - -
AEDC B	10	1650	3.0-3.4
AEDC C	50	1910	2.5
Calspan – HST	400	3900	1.8
AEDC HR	590	7200	1.8
NSWC T-9	20-40	2100	2.1-2.4
Calspan–HEDI	30-40	2100	2.65-2.85

Effect of Freestream Turbulence

Another consideration in the window-cooling testing is the effect of facility freestream turbulence on the test data. Successful turbulence measurements have not yet been made in these high-enthalpy flows. Efforts to match the arc heater bulk enthalpy with the enthalpy inferred from probe measurements show that something less than 5 percent freestream turbulence will reconcile the measurements. The effect of freestream turbulence on film cooling was reviewed briefly by Goldstein in Ref. 2. Carlson and Talmor[4] increased the freestream turbulence intensity from 3 to 22 percent and saw a significant decrease in its effectiveness at large distances downstream of the injection point. Kacker and Whitelaw[5] changed the turbulence intensity of the secondary gas in the injection slot from 5.5 to 9.5 percent and found no significant change in film-cooling effectiveness. Hence a freestream turbulence level of 5 percent or less would not be expected to have an appreciable effect. This expectation is borne out by the fact that no effect is apparent in the HR-HEDI data.

Heat Flux

Heat flux levels for the various facilities are shown in Table 3. Note that only the HR and the Calspan HST test provided heat fluxes that approach that of flight. Heat fluxes in the other facilities are low by factors of 20 to 100. Furthermore, the duration of the Calspan HST test was not long enough to evaluate survivability. Hence the primary objective of 'survivability' (see Table 1) originally selected for the HR test was a necessary and appropriate one.

Current AEDC High-Enthalpy Test Capabilities

It has been shown that the window-cooling effectiveness correlation developed for the HEDI program is relatively insensitive to freestream Mach number and Reynolds number but does show a sensitivity to total temperature. In light of these facts, new developments in AEDC's large segmented arc heater H3 and in Tunnel 9 provide additional ground test capabilities for future AIT interceptor work. The advantages of these facilities with respect to window cooling testing will be discussed relative to the potential AIT trajectories shown in Fig. 8.

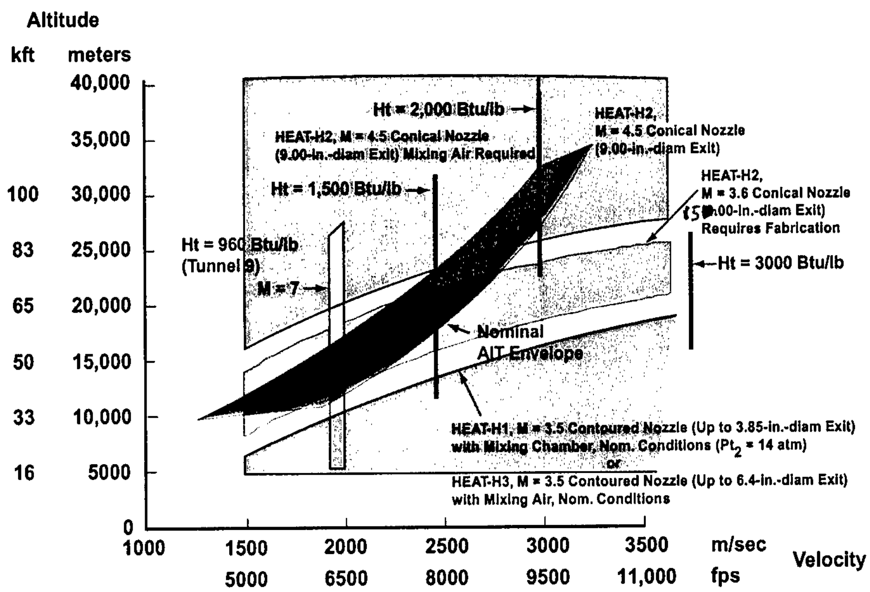


Fig. 8. AEDC capability comparison with nominal AIT flight envelope.

The Hypervelocity Wind Tunnel 9 Facility at White Oak, MD, provides aerodynamic simulation in critical altitude regimes associated with strategic offensive missile systems, advanced defensive interceptor systems, reentry vehicles, and hypersonic vehicle technologies. Tunnel 9 is a blowdown type facility with operational Mach numbers of 7, 8, 10, 14, and 16.5. This facility uses a unique storage heater which provides supply pressures up to 1430 atmospheres and supply temperatures up to 3460 degrees Rankine and sustains relatively long-duration, constant-condition runs. The AEDC Tunnel 9 facility (originally a Navy (NSWC) facility) has

added a Mach 7 nozzle which can duplicate flight conditions on the AIT trajectory midway between the maximum dynamic pressure point and the maximum heat-transfer point as indicated in Fig. 8. This facility has a core diameter of 8 in. of uniform, high-quality flow. Test times are on the order of seconds, which is short compared to arc-heated facilities, but long compared to shock tunnels.

The new 70-megawatt segmented arc heater, known as H3, significantly improves AEDC's present arc capabilities by providing larger flow areas. The flow-field cross-section from the H3 nozzle is nearly three times the area of AEDC's H1 arc heater. Arc heaters such as H3 produce the high pressures and heat fluxes required for testing thermal protection materials used for nosetips and heat shields during hypersonic flight.

AEDC also has an arc-heated wind tunnel in its inventory that can provide a large freejet (up to 24-in. diam) hypersonic flow. The tunnel, designated H2, uses air for true temperature and pressure simulations at velocities to 15,000 ft/sec and altitudes to 165,000 ft.

The maximum heat-transfer point shown on the AIT trajectory requires a high enthalpy for a thermal simulation and can be simulated with the AEDC arc facilities. The H1 arc heater with an existing nozzle can provide a 3-in.-diam flow field. A larger 3.85-in.-diam nozzle could be fabricated since mixing air is required to reduce the enthalpy to the flight enthalpy. The initial operational capability of H3 essentially maps to the H1 envelope, but can provide a 5-in.-diam flow at reentry level enthalphies, or a 6.4-in. diam flow for AIT at a reduced enthalpy of 1500 Btu/lbm with additional mixing air. The H2 facility can provide flight duplication at the higher altitudes experienced by the AIT while providing a large flow field. All the AEDC arc heater capabilities are summarized in Fig. 8, along with Tunnel 9.

Conclusions

It has been shown that the HR-HEDI film-cooling effectiveness data agree well with data from other ground test facilities and with the literature. Reevaluation of the data also shows the insensitivity of the correlation to freestream Mach number and Reynolds number. Extrapolation of the 'break-point' from datasets obtained at only highly cooled conditions will provide only a lower bound for the region of fully cooled flow. The uncertainties in extrapolating this correlation to flight conditions can be addressed through capabilities provided by AEDC high-enthalpy ground test facilities. The AEDC arc-heated facilities, H1, H2, and H3 can provide subscale and full-scale ground tests at total temperatures and heat fluxes representative of flight for velocities in the range from 1500 to 7000 m/sec and altitudes above 5000 meters. Tunnel 9, with the new nozzle, can provide a flight duplication Mach 7 test condition at full scale. In addition, the window-cooling correlation developed for the HEDI program has proven its validity for widely different geometries and test techniques and provides potential value for future programs. Finally, no one facility or flight test should be used as the only source of information relative to cooling effectiveness. Each facility has its place in providing a complete picture of the flight environment of a vehicle.

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